Did changes in the Subpolar North Atlantic trigger the recent mass loss from the Greenland Ice Sheet?

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The Greenland Ice Sheet's (GIS) contribution to sea level rise more than doubled in the last seven years due to a surprisingly rapid (and unpredicted) mass loss. The loss was not so much a result of increased surface melt but, rather, of ice loss due to the widespread and nearly-simultaneous acceleration of several outlet glaciers in Greenland's western and southeastern sectors [Rignot and Kanagaratnam, 2006]. Since Greenland's accelerating outlet glaciers terminate at tidewater in deep fjords and their floating ice shelves extend several hundreds of meters below sea-level it has been suggested that the acceleration may have been driven by oceanic changes [Bindschadler, 2006; Holland et al. 2008]. Specifically, increased melting due, for example, to warming ocean waters can speed up ice flow through a reduction of both the basal friction and the frontal buttressing to glacier flow. Indeed Greenland's accelerating glaciers lost their buttressing ice shelves either prior or during the acceleration. The ocean trigger hypothesis is empirically supported by the fact that the accelerating glaciers are located along the margins of the North Atlantic's subpolar gyre whose waters started to warm roughly at the same time as the glaciers began to accelerate [Bersch et al. 2007; Yashayaev et al. 2007]. Yet, the connection between Greenland's outlet glaciers and the large-scale subpolar ocean is new and far from obvious.

Outlet glaciers in Greenland terminate in deep, long fjords which end at the coast, over Greenland's shallow and broad shelf, a region dominated by cold, fresh waters of Arctic origin (PW), transported around Greenland by the East and West Greenland Currents (Figure 1a). Warm waters of subtropical origin (STW), on the other hand, are found on the continental slope in the core of the Irminger Current, an extension of the North Atlantic Current, or offshore in the gyre's interior. Evidence that STW penetrate inside Greenland's glacial fjords is limited to a handful of summer profiles from Jakobshavn [Holland et al. 2008] and Kangerdlugssuaq Fjords [Azetsu-Scott and Tan, 1997] making it impossible to assess if these waters are present year round, if they are present in other fjords and, in general, what their residence time is. More importantly, the rate of submarine melting depends on the heat transport to the glacier's terminus. Glacier acceleration could thus have been triggered by changes in the volume, properties and/or the circulation of STW in the fjords. Furthermore, several investigators have suggested that positive feedbacks associated with a classic estuarine-type circulation (increased melting driven by a warming ocean increases the estuarine circulation in the fjord which, in turn, draws more water in) may have played a role in amplifying the glaciers' response [Holland et al. 2008; Hanna et al. 2009]. Yet, there is presently no evidence that an estuarine-type circulation dominates in Greenland's glacial fjords. Identifying the processes that drive STW inside the fjords, and control their variability, is key to understanding the role of the ocean in triggering the ice sheet changes.

A recent study has provided evidence that very warm STW are not only present in large volumes in a major East Greenland glacial fjord but, also, that they are continuously replenished via rapid exchange with the shelf region [Straneo et al. 2009]. The study is based on observations collected in Sermilik Fjord where Helheim Glacier terminates (Figure 1a and b). Helheim Glacier is one of Greenland's largest outlet glaciers and has recently almost doubled its flow speed making it one of Greenland's fastest changing glaciers and a major contributor to sea-level rise [Howat et al. 2005; Stearns and Hamilton, 2007]. Large volumes of STW were observed inside the fjord and on the shelf, both in July and September 2008, Figure 2. Changes in water properties from July to September, velocity measurements and data from two moorings, deployed mid-fjord for the period in-between the surveys, allowed Straneo and colleagues to conclude that Sermilik Fjord is continuously and rapidly exchanging waters with the shelf. The exchange is driven by northeasterly wind events which 'pile up' water at the mouth of the fjord and result in large, strongly-sheared flows inside the fjord. This circulation, which is typical of narrow fjords, tends to be an order of magnitude larger than the classic estuarine circulation and, as such, is much more effective in transporting heat into the fjord [Klinck et al. 1981; Stigebrandt 1990]. Given the temperature of the waters inside Sermilik and their rapid renewal, combined with the fact that Helheim's terminus extends 500-700 m below sea-level, Straneo and colleagues conclude that, at present, ocean waters are driving substantial submarine melting of Helheim. Furthermore, since the conditions that allow STW to penetrate in Sermilik – its presence on the shelf and along-shore winds – are typical of both E. and W. Greenland, Straneo et al. speculate that ocean waters are likely driving substantial melting at the termini of other outlet glaciers along southeastern and western Greenland.

These findings are supportive of the ocean trigger hypothesis but not conclusive until it is shown that conditions were different prior to the last decade such that submarine melting was greatly reduced. Lack of historical data from Sermilik and other glacial fjords, however, makes it difficult to determine what conditions were like in the past. Some clues of what may have changed, at the same time, are provided by the findings of this new study. First, it seems unlikely that the warming of the STW alone (~ 1 ºC; Thierry et al., 2008) may have been responsible for the change since it is smaller than the seasonal temperature change observed by Straneo and colleagues in the fjord or on the shelf. Second, along-shore winds are typical along Greenland coasts [Moore and Renfrew, 2005], making it unlikely that the driver for fjord/shelf exchange was absent in the past. It seems more likely, then, that what has changed is that large volumes of warm STW are presently found on southern Greenland's continental shelves. This notion is supported by a number of recent observations (e.g. Sutherland and Pickart, 2008) and by repeat sections collected along the W. Greenland shelf showing that waters there were much colder prior to the mid-1990s [Holland et al. 2008; Hanna et al. 2009]. Also, while the mechanisms which allow STW to 'climb' onto Greenland's shelves are not clear – this idea is also consistent with the warming of the Irminger current and the subpolar gyre's interior [Myers et al. 2008; Yashayaev et al. 2007] and the gyre's slowdown [Häkkinen and Rhines, 2004] observed over the last decade.

This line of thought naturally leads to the question of what is driving the changes in the subpolar North Atlantic? The fact that the North Atlantic Oscillation (NAO), the dominant mode of variability over this region, switched from a persistent positive phase to a non-persistent phase in the mid-1990s (Figure 3a) has led some investigators to attribute the changes to the NAO alone (e.g. Holland et al. 2008). If this is true then the conclusion is that changes on the margins of the GIS may be driven by the NAO. Yet, there is increasing evidence that the changes in the subpolar region over the last decade are no longer attributable to the NAO alone. A recent study by Häkkinen and Rhines (2009), for example, attributes the anomalous inflow of STW into the subpolar region and Nordic Seas to changes in surface currents driven by shifting wind patterns which are no longer attributable to the NAO alone.

Further evidence of a lessening of the NAO's imprint on the North Atlantic is provided here in terms of the heat content of the North Atlantic. From historical data, we show that, until the mid-1990s, multidecadal fluctuations in heat content of the subpolar and subtropical regions were broadly consistent with shifts in the NAO through its impact on surface heat fluxes and cross-gyre exchanges between the subtropics and subpolar basins (Figure 3; Visbeck et al. 2003). Specifically, periods of negative (positive) NAO give rise to a warmer (cooler) subpolar and cooler (warmer) subtropical upper ocean and enhanced (reduced) northward flows of warm subtropical waters [Lozier et al. 2008]. This correlation, however, broke down in the mid-1990s and since then both the subtropical and subpolar regions have been gaining heat (Figure 3b) – something which can no longer be explained by the NAO alone.

In summary, we speculate that atmosphere/ocean changes since the mid-1990s have resulted in the unprecedented inflow of warm, subtropical waters around the subpolar region and on the Greenland shelves. These changes have been rapidly communicated to the glacial fjords through the wind-driven exchange between the fjord and the shelf and have played a significant role in accelerating outlet glaciers along the southeastern and western sectors. While more measurements at the ice-ocean edge are needed to understand the details of how these changes can effectively trigger an outlet glacier's acceleration, the idea that changes in the poleward heat transport (and the associated overturning circulation) of the North Atlantic can affect the Greenland Ice Sheet on such short time scales is new and has significant implications for our climate system. Monitoring of the warm inflow into the subpolar region, as well as on the Greenland shelves and inside the glacial fjords, combined with improved modeling of ice-sheet ocean interactions are necessary for us to understand a potentially highly significant and previously overlooked coupling within our climate system.

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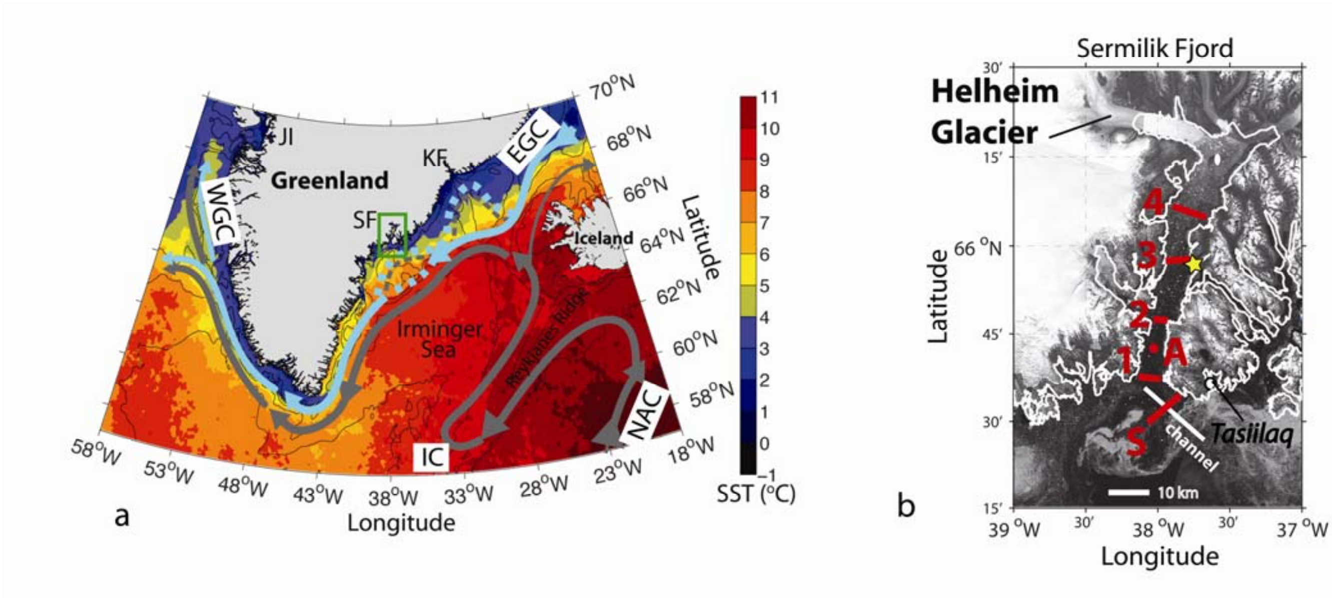

Figure 1 a) Main currents around southern Greenland overlaid on the 2003 mean sea-surface temperature (SST) from the Advanced Very High Resolution Radiometer (filled contours). Bathymetric contours (100, 500, 1000, 2000, 3000 m) are overlaid in black. Cold, polar waters (PW) are found over the shelf, transported by the EGC and WGC (dashed paths indicate multiple branches) and warm, subtropical waters (STW) are transported along the continental slope by the NAC and the IC. The approximate location of Sermilik Fjord (SF and green box), Kangerdlugssuaq Fjord (KF) and Jakobshavn Isbrae (JI) are indicated. b) A Landsat mosaic of Sermilik Fjord. Sections (1 to 4 and S) plus the single station A occupied during the 2008 surveys are indicated in red. The yellow star indicates the moorings location. *Figure is from Straneo et al. 2009.*

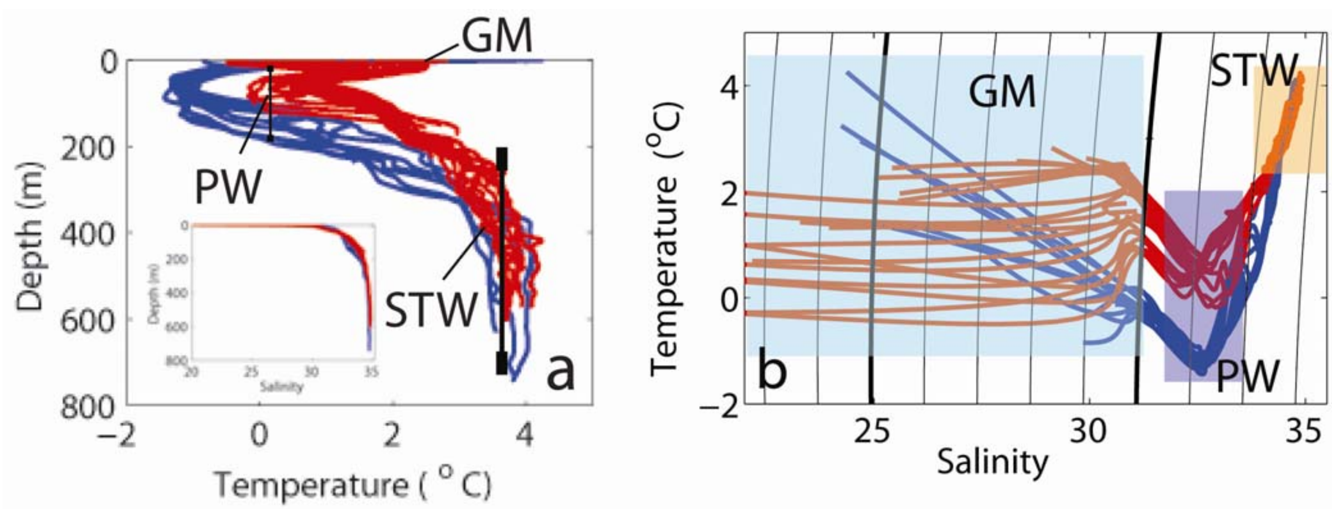

Figure 2. Ocean conditions in Sermilik Fjord in summer 2008. Three waters masses were observed in the fjord during both surveys: a thin (~10-20 m) glacial meltwater plume (GM), a 100-150 m thick layer of PW, and a thick layer of STW extending from approximately 200 m to the bottom. a) Potential temperature profiles in July (blue) and September (red); inset shows salinity. b) Potential temperature versus salinity for the two surveys (same colors as a)). The three water masses are indicated by the shaded boxes. Potential density contours are overlaid in black (thick lines are σ_θ=20 and 25 kg/m3). *Figure from Straneo et al. 2009.*

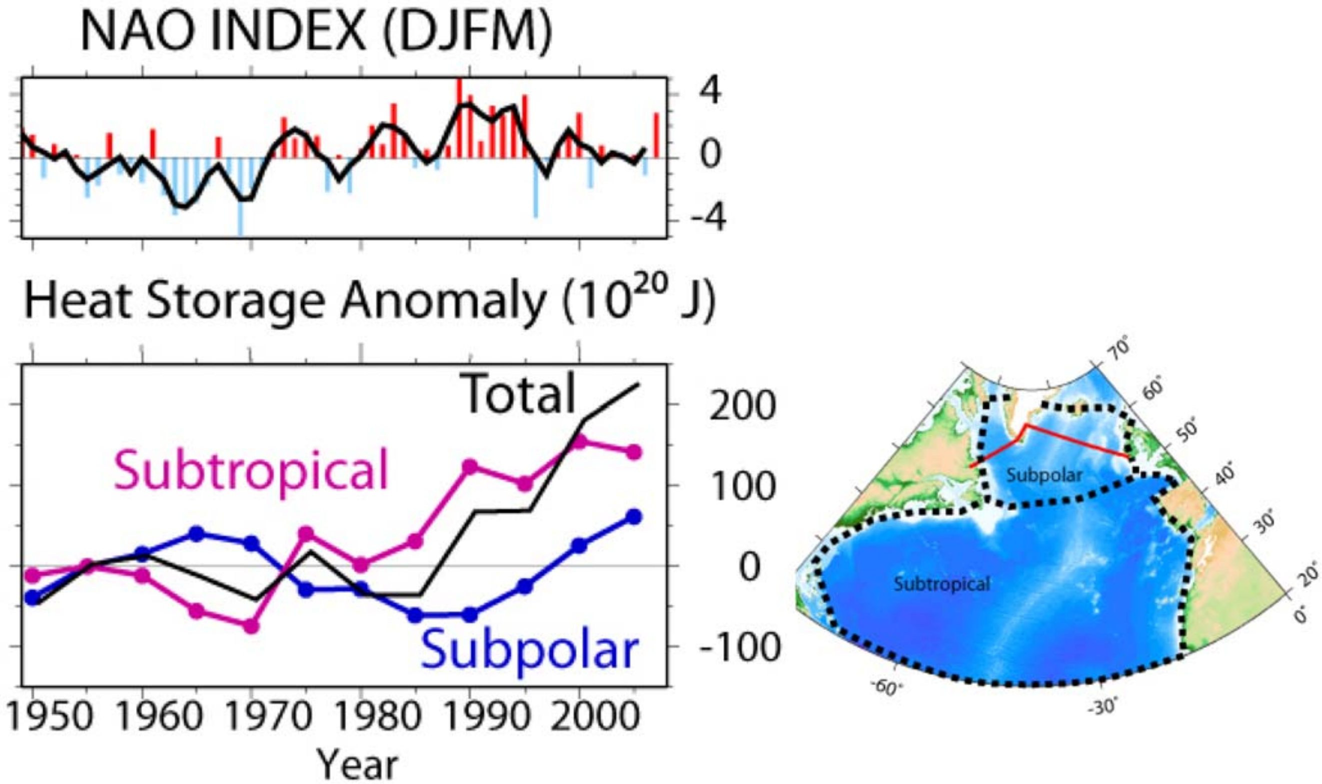

Figure 3 *Top panel*: Winter (Dec-Mar) NAO index shown as bars and a 3-year smoothed curve (http://www.cgd.ucar.edu/cas/jhurrell/) *Bottom Panel*: Time series of volumetric heat storage anomaly (10^{20} J) for the upper ocean (0-1200m) of the subtropical (20º-50º N), the subpolar (50º N to Davis Strait and the Greenland-Scotland Ridge) basins of the North Atlantic and for the two combined (basins are defined in map at right). Heat storage anomalies relative to 1955 were computed from 5-year averages of profile data (pressure, temperature, salinity) with the seasonal cycle removed. The data and analysis come from the *HydroBase2* package: http://www.whoi.edu/science/PO/hydrobase.

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